Electrostatic Precipitators

Modelling and Analytical Verification Concept

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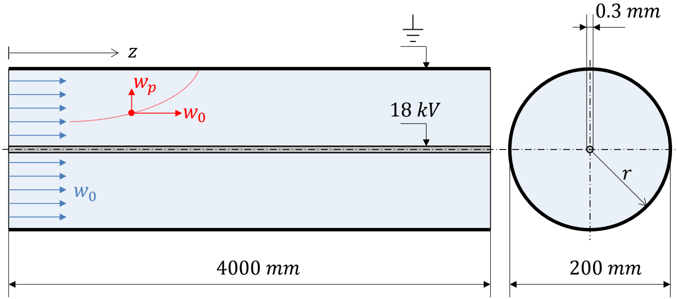
COMSOL CONFERENCE
2015 GRENOBLE

Outline

- Introduction
- Assumptions
- Electrostatics
- COMSOL Setup
- COMSOL Solution
- Analytical Verification
- Discussion
- Experimental Validation
- Summary

Introduction

Cutout of a wire-tube ESP



Assumptions

- spherical particles
- fluid (air) incompressible, ideal gas behavior, turbulent flow
- fully developed velocity profile
- isothermal flow
- buoyancy neglected
- convective and diffusive terms neglected
- free slip electrode

Electrostatics

Numerical Model

$$\nabla \cdot \boldsymbol{E} = \frac{\rho_{el}}{\varepsilon_0} \quad (1)$$

$$\boldsymbol{E} = -\nabla \phi \quad (2)$$

$$\nabla \cdot \boldsymbol{J} = 0 \quad (3)$$

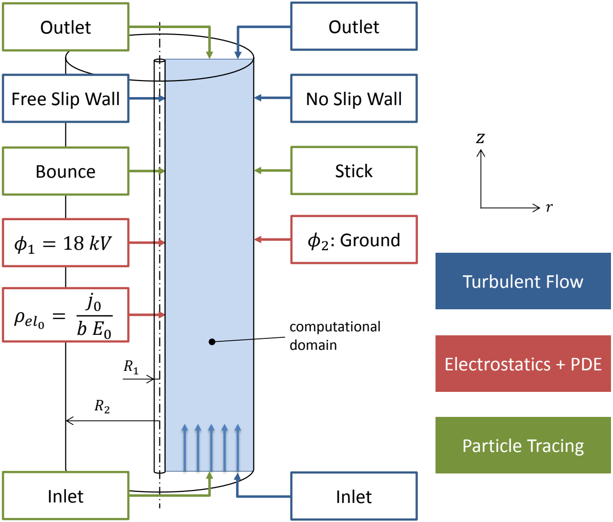
$$\boldsymbol{J} = \rho_{el}(\cancel{\boldsymbol{w}} + b\boldsymbol{E}) - \cancel{D\nabla\rho_{el}} \quad (4)$$

$$\nabla^2 \phi = -\frac{\rho_{el}}{\varepsilon_0} \quad (5)$$

$$\boldsymbol{E}\nabla\rho_{el} = -\frac{{\rho_{el}}^2}{\varepsilon_0} \quad (6)$$

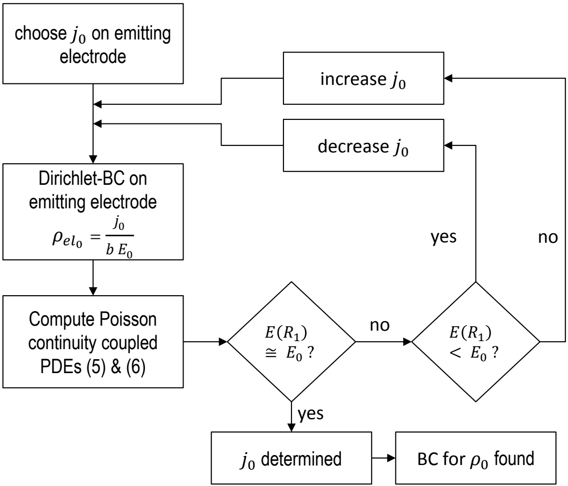
COMSOL Setup

Boundary Conditions



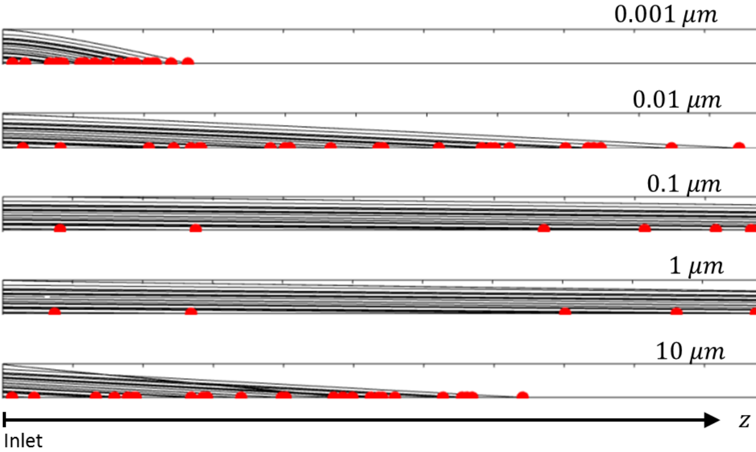
COMSOL Setup

Iteration Scheme



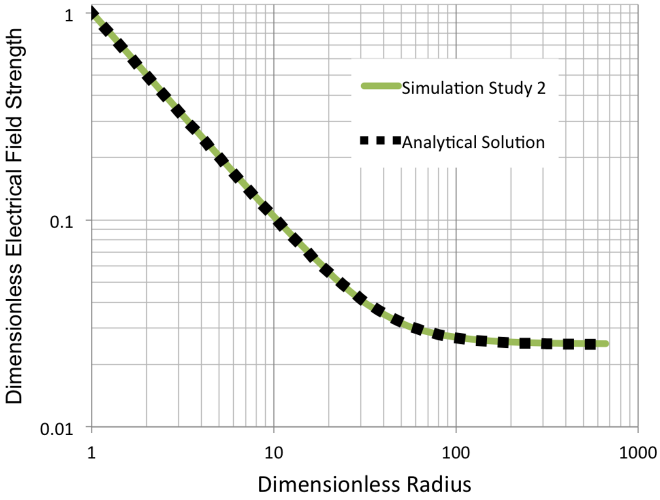
COMSOL Solution

Particle results



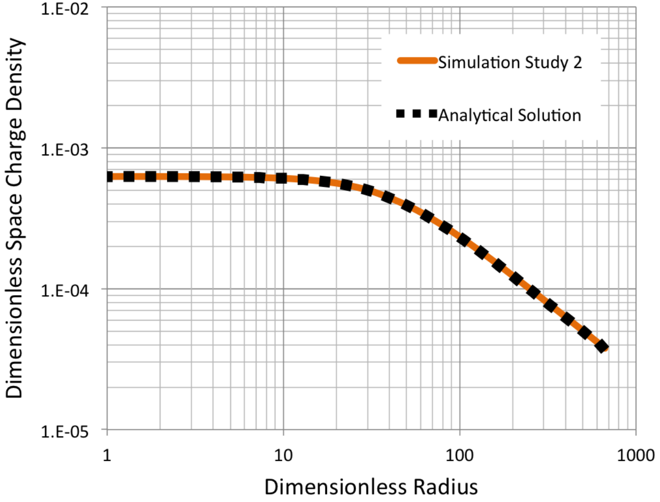
Analytical Verfication

Electric Field Strength along the radius



Analytical Verfication

Space Charge Density along the radius



Discussion

Flow Simulation

- no slip - BC on emitting electrode

COMSOL Setup

- iteration scheme - computation time efficient and robust
- automation of the iterative procedure - fully coupled approach (solver-tuning)
- include diffusion and convection in the physical model

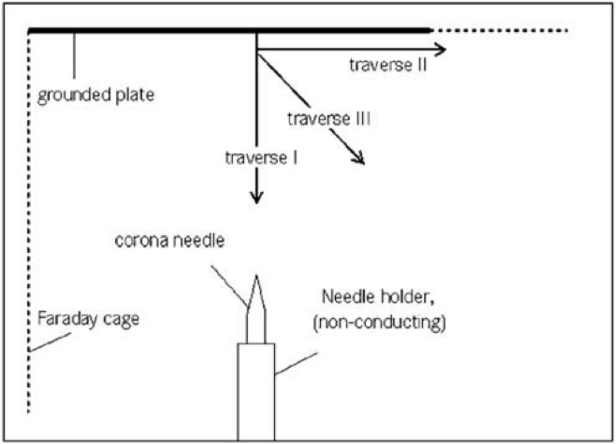
Analytical Verification

- physical model is *mathematically* correct
- experimental validation is delicate

Experimental Validation

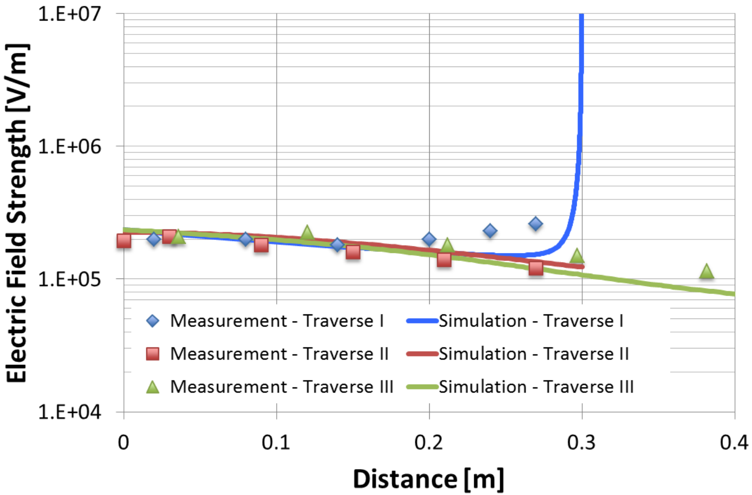
Adaptation to other geometries

Setup



Source: Poppner, Marc et al. (2005): Electric Fields coupled with ion space charge. Part 1 + 2. Journal of Electrostatics. Volume 63. S.775-787. Amsterdam: Elsevier.

Experimental Validation



Summary

Completed Points

- Simulation of an entire ESP including
  - Flow Simulation
  - Electrostatics + Charge Conservation
  - Particle Charging Processes
  - Particle Motion + Deposition Efficiency

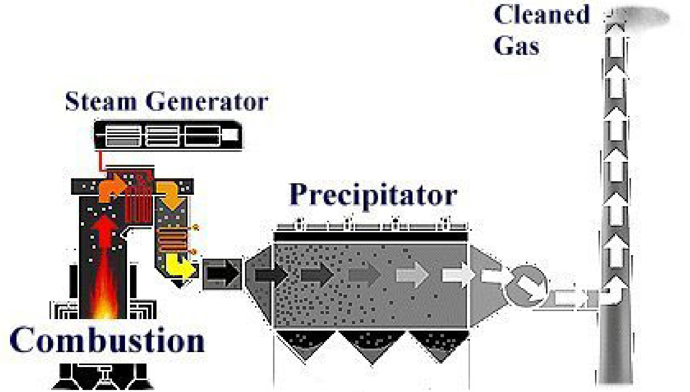
Conclusions

- Customizable code needed (user-defined PDEs)
- Concept numerically robust and practical
- Analytical verification appropiate
- Experimental validation quite delicate

Thank you for your attention.

Appendix

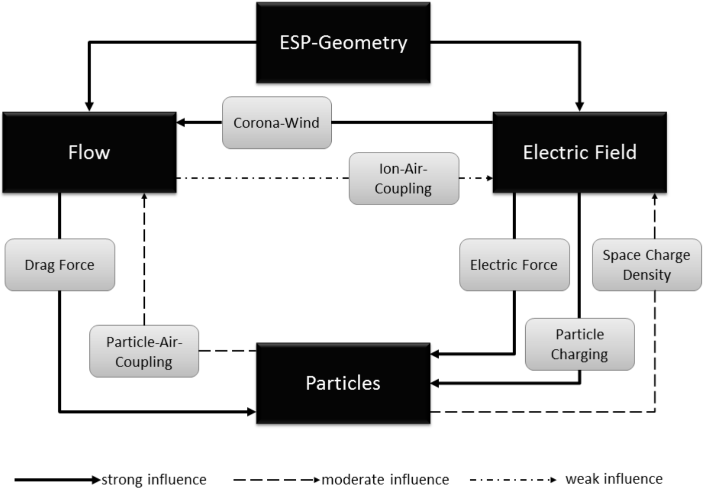
Industrial Standard



Source: http://www.neundorfer.com/knowledgebase/electrostaticprecipitators. Accessed on 13/10/2015

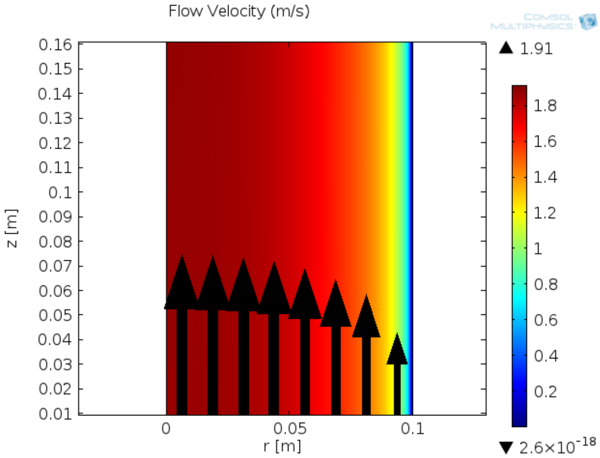
Appendix

Coupled Physics in ESPs



Appendix

Velocity Profile



Appendix

Dimensionless Equations

$$\frac{E}{E_\text{o}} = \hat{E} = \frac{1}{\hat{r}}\sqrt{1 + \hat{A}(\hat{r}^2 - 1)} \tag{7}$$

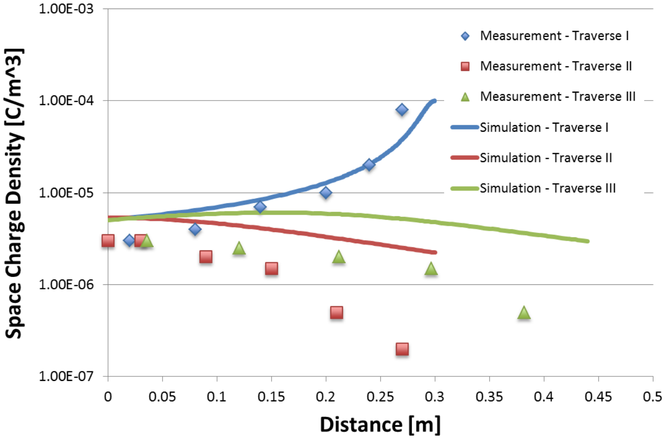
$$\frac{\rho_{el}}{\frac{\varepsilon_0 E_\text{o}}{r_E}} = \hat{\rho}_{el} = \frac{\hat{A}}{\sqrt{1 + \hat{A}(\hat{r}^2 - 1)}} \tag{8}$$

$$\hat{A} = \frac{j_\text{o} r_E}{\varepsilon_0 b {E_\text{o}}^2} \tag{9}$$

Appendix

Experimental Validation I

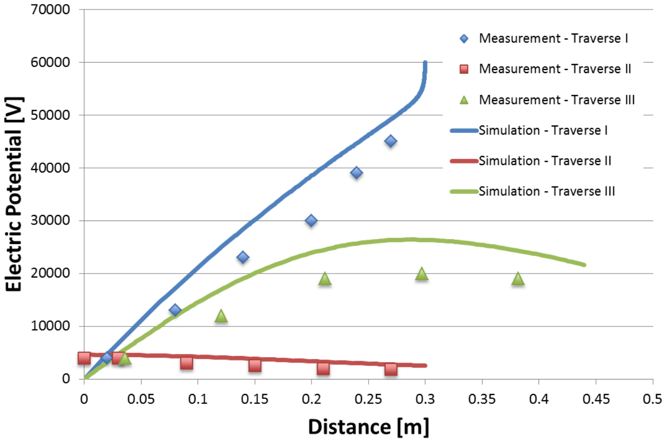
Space Charge Density



Appendix

Experimental Validation II

Electric Potential



Appendix

Maxwells Equations

$$\nabla \cdot \boldsymbol{D} = \rho_{el} \tag{10}$$

$$\nabla \times \boldsymbol{H} - \frac{\partial \boldsymbol{D}}{\partial t} = \boldsymbol{J} \tag{11}$$

$$\nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} = 0 \tag{12}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{13}$$

Appendix

Schiller-Naumann Drag Model

$$F_D = \frac{1}{\tau_p} m_p w_p \tag{14}$$

$$\tau_p = \frac{4 \rho_p {d_p}^2}{3 \mu C_D Re_p} \tag{15}$$

$$C_D = \frac{24}{Re_p}(1 + 0.15 {Re_p}^{0.637}) \tag{16}$$

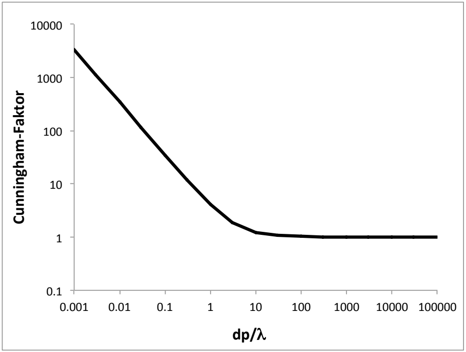
$$Re_p = \frac{\rho w_p d_p}{\mu} \tag{17}$$

Appendix

Cunningham Coefficient

$\lambda \sim 10^{-8}$m

$$C_c = 1 + \frac{\lambda}{d_p}\Big[2.34 + 1.05\ exp\Big(-0.39\frac{d_p}{\lambda}\Big)\Big] \qquad (18)$$



Appendix

Deposition Efficiency

$$\eta_{ESP} = 1 - \frac{N_{out}}{N_0} = 1 - exp\left(\frac{-w_p A_c}{\dot{V}}\right) \qquad (19)$$

Appendix

Corona Onset Field Strength

$$E_0 = 3 \times 10^6 f_r \left(m_s + 0.03 \sqrt{\frac{m_s}{\frac{d_e}{2}}} \right) \tag{20}$$

$$m_s = \frac{p}{p_{ref}} \frac{T_{ref}}{T} \tag{21}$$

Appendix

Particle Charging Processes

Diffusion Charging

$$q_d(t) = \frac{2\pi\varepsilon_0 kTd_p}{e} ln\left(1 + \frac{t}{\tau_d}\right) \tag{22}$$

Field Charging

$$q_f(t) = \left(\frac{3\varepsilon}{\varepsilon + 2}\right)\pi\varepsilon_0 E{d_p}^2 \frac{t}{t + \tau_f} \tag{23}$$

Appendix

Demo (Source: youtube.com/pentenrieder)

Appendix
Demo

Appendix

Demo

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Demo

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Demo